

Implications of first LHC results

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We discuss implications of first LHC results for models motivated by the hierarchy problem: large extra dimensions and supersymmetry. We present bounds, global fits and implications for naturalness.

1 Introduction

The main goal of the LHC is telling us why the weak scale is much below the Planck scale: this hierarchy problem was adopted in the past 30 years as guideline of many theoretical works. Maybe LHC will tell which CMSSM parameters are right. Or maybe LHC will tell which SUSY model is right. Or maybe LHC will tell which solution to the hierarchy problem is right. Or maybe LHC will tell that the hierarchy problem is not a good guideline.

The way to make progress is searching for the signals predicted by tentative solutions. We here discuss implications of first LHC results on two of these proposals: supersymmetry and large extra dimensions.

2 Large extra dimensions

The hierarchy problem can be solved assuming that the quantum gravity scale M_D is around the weak scale, and that the larger Planck scale arises because gravitons live in δ extra dimensions¹. The following unavoidable collider signals of this scenario have been proposed:

1. Graviton emission (accompanied by a jet to tag the event).
2. Virtual graviton exchange, which gives the dimension 8 operator $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + 8\mathcal{T}/M_{\mathcal{T}}^4$, $M_{\mathcal{T}}$ is expected to be comparable to M_D , $\mathcal{T} = T_{\mu\nu}^2/2$, and $T_{\mu\nu}$ is the SM energy-momentum tensor.
3. Virtual graviton exchange at one loop level, which gives the dimension 6 operator $\Upsilon = (\sum_f \bar{f} \gamma_\mu \gamma_5 f)^2/2$.
4. The previous signals are computable at low energy, $E \ll M_D$. Other computable signals (such as black-hole production) arise in the opposite limit $E \gg M_D$, which is presumably not relevant for LHC.

In view of the high dimensionality of the operator \mathcal{T} , its effect grows fast with energy such that LHC (thanks to its increased energy) is more sensitive than all previous colliders, already with

Experiment	Process	+	-
LEP	$e^+e^- \rightarrow \gamma\gamma$	0.93 TeV	1.01 TeV
LEP	$e^+e^- \rightarrow e^+e^-$	1.18 TeV	1.17 TeV
CDF	$p\bar{p} \rightarrow e^+e^-, \gamma\gamma$	0.99 TeV	0.96 TeV
DØ	$p\bar{p} \rightarrow e^+e^-, \gamma\gamma$	1.28 TeV	1.14 TeV
DØ	$p\bar{p} \rightarrow jj$	1.48 TeV	1.48 TeV
CMS at 7 TeV with 34/pb	$pp \rightarrow \gamma\gamma$	1.72 TeV	1.70 TeV
CMS at 7 TeV with 40/pb	$pp \rightarrow \mu^-\mu^+$	1.6 TeV	1.6 TeV
ATLAS at 7 TeV with 36/pb	$pp \rightarrow jj$	4.2 TeV	3.2 TeV
ATLAS at 7 TeV with 3.1/pb	$pp \rightarrow jj$	2.2 TeV	2.1 TeV
CMS at 7 TeV with 36/pb	$pp \rightarrow jj$	4.2 TeV	3.4 TeV

Table 1: Limits on virtual graviton exchange for positive and negative interference with the SM amplitude.

integrated luminosity much lower than previous colliders. The operator \mathcal{T} contributes to various cross sections:

$$\sigma = \left(\frac{2 \text{ TeV}}{M_{\mathcal{T}}}\right)^8 \times \begin{cases} 12.5 \text{ pb} & \text{for } pp \rightarrow jj \\ 10.4 \text{ fb} & \text{for } pp \rightarrow \mu^+\mu^- \\ 21.3 \text{ fb} & \text{for } pp \rightarrow \gamma\gamma \end{cases}$$

The $pp \rightarrow jj$ channel² was ignored because jets have more background than leptons or photons; but it has a much larger cross-section, and this is the most important aspect at LHC startup, with poor integrated luminosity. As summarized in table 1, already with 3/pb LHC data about $pp \rightarrow jj$ provided the dominant constraint³.

Since quantum corrections to the higgs mass are made finite by unknown aspects of quantum gravity, we cannot tell if the LHC bound $M_{\mathcal{T}} > 3.4 \text{ TeV}$ got so strong that large extra dimensions no longer are a good solution to the hierarchy problem.

3 Supersymmetry

In supersymmetry quantum corrections to the higgs mass are made finite by sparticle loops. Thereby there is neat connection between sparticle masses and the weak scale:

$$M_Z^2 \approx 0.2m_0^2 + 0.7M_3^2 - 2\mu^2 = (91 \text{ GeV})^2 \times 80 \left(\frac{M_3}{1 \text{ TeV}}\right)^2 + \dots \quad (1)$$

where we assumed the CMSSM (Constrained Minimal Supersymmetric Standard Model) and fixed $\tan\beta = 3$, $A_0 = 0$, like in the experimental analyses that presented first LHC bounds on such supersymmetric model⁴.

The order one coefficient of M_3^2 arises due to RGE running from the GUT scale down to the weak scale, and thereby is generic of models where SUSY breaking is present at such high scale.

As a consequence of the LHC bound on the gluino mass M_3 , its contribution to M_Z^2 is almost 100 times too large, and needs to be canceled by other terms giving rise to a fine-tuning problem. Within the CMSSM, supersymmetry allows to reduce the SM higgs mass fine tuning from $\sim 10^{30}$ down to ~ 100 only: no longer down to ~ 1 , casting doubts on the ideology according to which the hierarchy problem is solved identifying the weak scale with the SUSY-breaking scale.

To be more precise, eq. (1) can be used to eliminate one parameter, such that the CMSSM model has two free parameters. Instead of the usual choice, m_0 and $M_{1/2} \approx M_3/2.6$, we choose any two adimensional ratios, such that the overall scale of supersymmetry is fixed by eq. (1), rather than by hand. Only in the part of the parameter space where cancellations happen, sparticles are heavier than M_Z (their natural scale according to eq. (1)) and compatible with

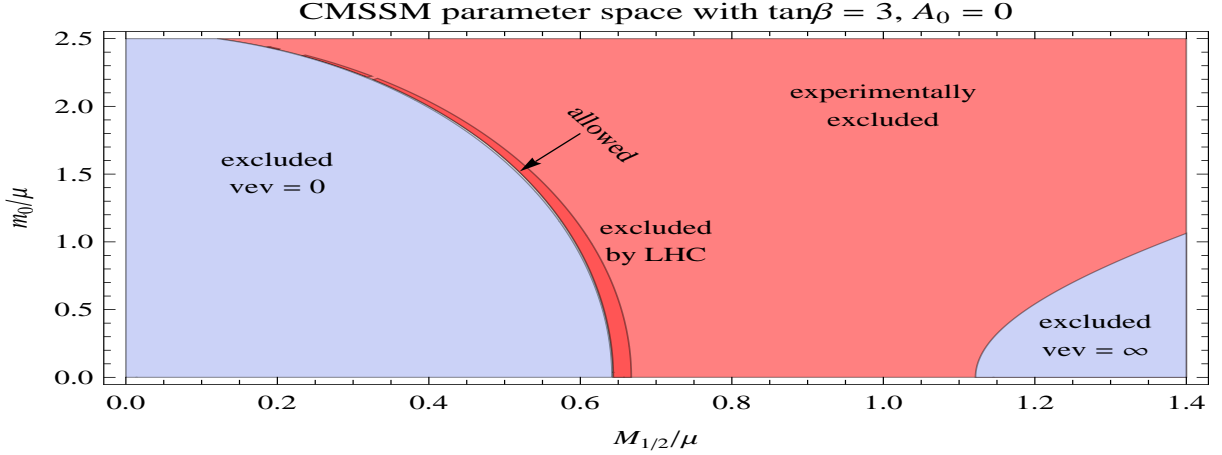


Figure 1: An example of the parameter space of the CMSSM model. The white region is allowed. The dashed line around the boundary of the allowed region is the prediction of the BS model.

experimental bounds. The result is shown in fig. 1 from ⁷ (here updated at the light of the latest ATLAS data with 165/pb⁵).

- The light-gray regions are theoretically excluded because the minimum of the potential is not the physical one.
- The red region in the middle is theoretically allowed, but it has now been experimentally excluded. The darker red shows the new region excluded by LHC with respect to the previous LEP bounds.
- The white region is allowed, but is now so small that enlarging the picture is needed to see it. It is close to the boundary where $M_Z = 0$ and thereby has $M_Z \ll m_0, M_{1/2}, \mu$.

So far we fixed $A_0 = 0$ and $\tan \beta = 3$, but the situation within this slice of parameter space is representative of the situation present in the full CMSSM parameter space. To explore it we scan all its adimensional parameters, and compute the allowed “fraction of parameters space”, which generalized the “size of the allowed region” in fig. 1. We find that only about 0.7% of the CMSSM parameter space remains allowed. Furthermore non-minimal Higgs models invented to ameliorate the analogous issue already present after LEP no longer work, just because the LHC bound has nothing to do with the higgs (see table 2).

LEP excluded sparticles around the Z mass. LHC now excludes heavier sparticles, and reaches the next milestone: sparticles a loop factor above M_Z . Indeed the dashed line in fig. 1 is the prediction of a model where the usual relation, eq. (1), gets supplemented by a relation that demands sparticle to be a loop factor above M_Z : $m_{\tilde{t}} \approx 4\pi M_Z / \sqrt{12}$ ⁶.

Ignoring the naturalness issue, first data from LHC also affect CMSSM global fits⁸, where the scale of supersymmetry is now fixed by i) fitting the anomaly in the $g - 2$ of the muon

experimental bound	fraction of surviving CMSSM parameter space		
	any m_h	$m_h > 100 \text{ GeV}$	$m_h > 110 \text{ GeV}$
LEP	10%	3%	1%
LHC	2.2%	1.2%	0.7%

Table 2: Fraction of the CMSSM parameter space that survives to the various bounds.

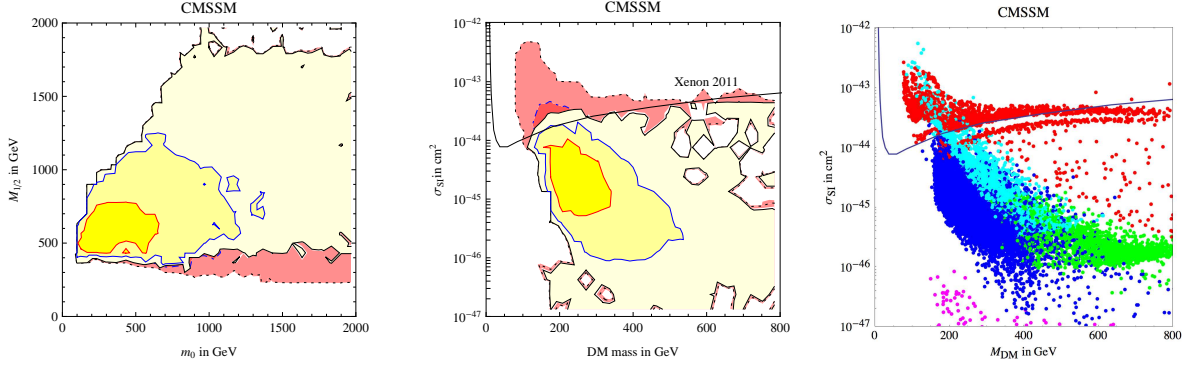


Figure 2: Global CMSSM fit updated to 165/pb of ATLAS data.

compatibly with other indirect data; ii) demanding that the thermal abundance of the lightest neutralino equals the Dark Matter abundance.

Fig. 2a shows the results: LHC has a minor impact, eliminating the part of the best-fit parameter space with lighter sparticles. Furthermore the recent Xenon-100 search for direct detection of Dark Matter⁹ disfavors the region in pink in fig. 2a and b. To understand what is this region now disfavored, fig. 2c shows that the best CMSSM fit is made of a few qualitatively different corners of the CMSSM parameter space, corresponding to different ad hoc mechanisms that allow to reproduce the DM abundance:

- The now disfavored red dots correspond to the “well tempered bino-higgsino” mechanism i.e. $M_1 \sim |\mu|$, that in the CMSSM is possible for large m_0 .
- The most natural DM annihilation mechanism (neutralino annihilations into sleptons) has been excluded because light enough sleptons are no longer allowed within the CMSSM.
- The “higgs-resonance” mechanism for enhanced DM annihilation, i.e. light $M_{\text{DM}} \approx m_h/2$ and consequently a relatively light gluino, was allowed in the previous global fit⁸. It has now been excluded by the new ATLAS CMSSM bounds⁵.
- The remaining allowed mechanisms are: slepton co-annihilations (blue dots), H or A resonance (green dots), h, H, A mediation at large $\tan \beta$ (cyan dots), stop co-annihilations (magenta dots).

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